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## RESEARCH PAPER

# AMP-activated protein kinase inhibits $K_v1.5$ channel currents of pulmonary arterial myocytes in response to hypoxia and inhibition of mitochondrial oxidative phosphorylation

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## Key points

- Progression of hypoxic pulmonary hypertension is thought to be due, in part, to suppression of voltage-gated potassium channels ( $K_v$ ) in pulmonary arterial smooth muscle by hypoxia, although the precise molecular mechanisms have been unclear.
- AMP-activated protein kinase (AMPK) has been proposed to couple inhibition of mitochondrial metabolism by hypoxia to acute hypoxic pulmonary vasoconstriction and progression of pulmonary hypertension.
- Inhibition of complex I of the mitochondrial electron transport chain activated AMPK and inhibited  $K_v1.5$  channels in pulmonary arterial myocytes.
- AMPK activation by 5-aminoimidazole-4-carboxamide riboside, A769662 or C13 attenuated  $K_v1.5$  currents in pulmonary arterial myocytes, and this effect was non-additive with respect to  $K_v1.5$  inhibition by hypoxia and mitochondrial poisons.
- Recombinant AMPK phosphorylated recombinant human  $K_v1.5$  channels in cell-free assays, and inhibited  $K^+$  currents when introduced into HEK 293 cells stably expressing  $K_v1.5$ .
- These results suggest that AMPK is the primary mediator of reductions in  $K_v1.5$  channels following inhibition of mitochondrial oxidative phosphorylation during hypoxia and by mitochondrial poisons.

**Abstract** Progression of hypoxic pulmonary hypertension is thought to be due, in part, to suppression of voltage-gated potassium channels ( $K_v$ ) in pulmonary arterial smooth muscle cells that is mediated by the inhibition of mitochondrial oxidative phosphorylation. We sought to determine the role in this process of the AMP-activated protein kinase (AMPK), which is intimately coupled to mitochondrial function due to its activation by LKB1-dependent phosphorylation in response to increases in the cellular AMP:ATP and/or ADP:ATP ratios. Inhibition of complex I of the mitochondrial electron transport chain using phenformin activated AMPK and inhibited  $K_v$  currents in pulmonary arterial myocytes, consistent with previously reported effects of mitochondrial inhibitors. Myocyte  $K_v$  currents were also markedly inhibited upon AMPK activation by A769662, 5-aminoimidazole-4-carboxamide riboside and C13 and by intracellular dialysis from a patch-pipette of activated (thiophosphorylated) recombinant AMPK heterotrimers ( $\alpha 2\beta 2\gamma 1$  or  $\alpha 1\beta 1\gamma 1$ ). Hypoxia and inhibitors of mitochondrial oxidative phosphorylation reduced AMPK-sensitive  $K^+$  currents, which were also blocked by the selective  $K_v1.5$  channel inhibitor diphenyl phosphine oxide-1 but unaffected by the presence of the  $BK_{Ca}$

channel blocker paxilline. Moreover, recombinant human  $K_v1.5$  channels were phosphorylated by AMPK in cell-free assays, and  $K^+$  currents carried by  $K_v1.5$  stably expressed in HEK 293 cells were inhibited by intracellular dialysis of AMPK heterotrimers and by A769662, the effects of which were blocked by compound C. We conclude that AMPK mediates  $K_v$  channel inhibition by hypoxia in pulmonary arterial myocytes, at least in part, through phosphorylation of  $K_v1.5$  and/or an associated protein.

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**Abbreviations** AICAR, 5-aminoimidazole-4-carboxamide riboside; AMPK, AMP-activated protein kinase;  $BK_{Ca}$ , large conductance voltage- and calcium-activated  $K^+$  channel; DPO-1, diphenyl phosphine oxide-1; HEK 293, human embryonic kidney 293 cells; HPV, hypoxic pulmonary vasoconstriction;  $K_v$ , voltage-gated  $K^+$  channel; LKB1, liver kinase B1.

## Introduction

Hypoxia without hypercapnia induces pulmonary vasoconstriction, and thus assists ventilation–perfusion matching in the lung (von Euler & Liljestrand, 1946). However, hypoxia may trigger pulmonary hypertension when it is widespread, for example during ascent to altitude (Bartsch *et al.* 2005) or due to disorders such as cystic fibrosis (Lahm *et al.* 2014). While current therapies have been shown to prolong survival, pulmonary hypertension remains a life-threatening disorder (Lahm *et al.* 2014) and the precise molecular mechanisms underlying it remain unclear. Therefore, greater understanding is critical to the development of effective therapies.

Initially, hypoxic pulmonary vasoconstriction (HPV) is driven by calcium release via ryanodine receptors from the sarcoplasmic reticulum of pulmonary arterial smooth muscle cells (Dipp *et al.* 2001), but is also associated with concomitant inhibition of voltage-gated potassium channels ( $K_v$ ) (Post *et al.* 1992; Yuan *et al.* 1993; Archer *et al.* 2004). The role of  $K_v$  channel inhibition in acute HPV remains open to debate (Wilson *et al.* 2002; Wang *et al.* 2004; Evans *et al.* 2005; Lu *et al.* 2008), but it has been proposed that loss of  $K_v$  function contributes to smooth muscle proliferation and thus to the progression of pulmonary hypertension (Sweeney & Yuan, 2000; Moudgil *et al.* 2006) by promoting cell survival (Ekhterae *et al.* 2001, 2003).

$K_v$  current suppression during hypoxia (Post *et al.* 1992; Yuan *et al.* 1993; Firth *et al.* 2008) occurs as a consequence of inhibition of mitochondrial oxidative phosphorylation (Firth *et al.* 2008, 2009). However, the nature of the signalling pathway that couples mitochondrial function to  $K_v$  channels has been unclear. In this respect, little attention has been paid to the role of the AMP-activated protein kinase (AMPK), although we have previously proposed that it couples inhibition of mitochondrial metabolism by hypoxia to acute HPV (Evans *et al.* 2005; Evans, 2006) and may also contribute to the progression

of pulmonary hypertension (Evans *et al.* 2005; Evans, 2006; Ibe *et al.* 2013; Goncharov *et al.* 2014). AMPK, an energy sensor that acts to maintain cellular energy homeostasis, exists as heterotrimers comprising catalytic  $\alpha$  subunits and regulatory  $\beta$  and  $\gamma$  subunits (Hardie, 2014a,b,c). AMPK is coupled to mitochondrial metabolism through changes in the cellular AMP:ATP and ADP:ATP ratios. Binding of AMP to the  $\gamma$  subunit causes a 10-fold increase in AMPK activity by allosteric activation, but a further activation of up to 100-fold can be generated by binding of either AMP or ADP, which promotes phosphorylation and inhibits dephosphorylation of Thr172 on the  $\alpha$  subunit; these effects are antagonised by ATP (Gowans *et al.* 2013; Ross *et al.* 2016). Thr172 is primarily phosphorylated by the tumour suppressor kinase LKB1 (liver kinase B1), which appears to be constitutively active (Sakamoto *et al.* 2004), but which phosphorylates AMPK more rapidly when AMP is bound to the  $\gamma$  subunit. In an alternative  $Ca^{2+}$ -dependent activation mechanism, the calmodulin-dependent protein kinase  $CaMKK\beta$  can also phosphorylate Thr172 and hence activate AMPK in an AMP-independent manner (Hardie, 2014a,b,c). The classical role of AMPK is to maintain energy homeostasis under conditions of metabolic stress, by activating catabolic processes that generate ATP and inhibiting non-essential anabolic processes that consume ATP. However, AMPK has also been shown to regulate a wide variety of ion channels and membrane transport proteins (Evans *et al.* 2009; Lang & Foller, 2014), including  $K_v2.1$  (Ikematsu *et al.* 2011),  $KCa3.1$  (Ross *et al.* 2011), and Kir 2.1 and  $K_v7.1$  (Lang & Foller, 2014).

Of the various known  $K_v$  channel types, it has been established that both  $K_v2.1$  and  $K_v1.5$  contribute to voltage-gated potassium currents in pulmonary arterial myocytes (Smirnov *et al.* 2002; Archer *et al.* 2004; Firth *et al.* 2011; Olschewski *et al.* 2014). Their relative contributions vary in a manner related to arterial diameter, with the greatest level of  $K_v1.5$  expression (and contribution to  $K_v$  currents) occurring in myocytes from

near-resistance-sized arteries (Archer *et al.* 1998, 2004; Smirnov *et al.* 2002; Moral-Sanz *et al.* 2011), the response of which to hypoxia is critical to acute increases in pulmonary arterial perfusion pressure. Moreover, selective down-regulation of  $K_v1.5$  has been identified as a hallmark of pulmonary hypertension (Yuan *et al.* 1998; Michelakis *et al.* 2002; Bonnet *et al.* 2006; Remillard *et al.* 2007; Burg *et al.* 2010; Morales-Cano *et al.* 2014). Consistent with this view, overexpression of  $K_v1.5$  enhances apoptosis (Brevnova *et al.* 2004), while adenoviral expression of a  $K_v1.5$  transgene *in vivo* reduces pulmonary hypertension and restores HPV (Pozeg *et al.* 2003).

We show here that AMPK selectively inhibits  $K_v1.5$  in pulmonary arterial myocytes, and also phosphorylates and inhibits recombinant  $K_v1.5$  channels expressed in HEK 293 cells.

## Methods

### Ethical approval

All experiments were performed under the United Kingdom Animals (Scientific Procedures) Act 1986. The animals used in this study were male Sprague Dawley rats that underwent no experimental procedures as recognised under UK Law. They were killed using a Schedule 1 method for collection of tissues only, which does not require formal ethical approval in the UK. Frozen canine tissue was left over from a previous project where surgical procedures and protocols were approved by the Cleveland Clinic Foundation Institutional Animal Care and Use Committee (Cleveland, OH, USA).

### Smooth muscle cell isolation

Resistance pulmonary arteries ( $<200\ \mu\text{m}$  inner diameter) from male Sprague Dawley rats (250–350 g) were dissected into a physiological bath solution of composition (in mM): NaCl 135, KCl 5,  $\text{MgCl}_2$  1,  $\text{CaCl}_2$  1, glucose 10, Hepes 10 (pH 7.4). For cell isolation, endothelium denuded arteries were transferred into a nominally calcium-free bath solution containing (in  $\text{mg ml}^{-1}$ ): 1 papain, 0.8 dithiothreitol and 0.7 BSA. The tissue was incubated in the latter solution for 10 min at  $37^\circ\text{C}$  and gently triturated using a fire polished glass pipette to get dispersed pulmonary arterial smooth muscle cells.

### Electrophysiological recordings

Pulmonary arterial myocytes or HEK 293 cells that stably expressed  $K_v1.5$  were transferred to a recording chamber and perfused at  $1\ \text{ml min}^{-1}$  with bath solution.  $\text{K}^+$  currents were recorded by whole-cell patch clamp and a pipette solution of the following composition (mM): KCl 140,  $\text{MgCl}_2$  1, EGTA 10, Hepes 10,  $\text{Na}_2\text{ATP}$  4,  $\text{Na}_3\text{GTP}$  0.1 (pH 7.2). Cells were superfused ( $3\ \text{ml min}^{-1}$ ) at

$37^\circ\text{C}$  with bath solution steadily bubbled with either room air (normoxia) or 95%  $\text{N}_2/5\%$   $\text{CO}_2$  [hypoxia,  $4.4 \pm 0.3\%$   $\text{O}_2$  in the experimental chamber; as measured with an optical oxygen meter (FireStingO2, Pyro Science, Aachen, Germany)]. For some experiments recombinant thiophosphorylated AMPK heterotrimers ( $\alpha 2\beta 2\gamma 1$ ,  $\alpha 1\beta 1\gamma 1$  or D157A kinase dead mutant) were added to the pipette solution.  $K_v$  currents were assessed by voltage ramps ( $-100$  to  $+40\ \text{mV}$ ), single voltage steps ( $-80$  to  $+40\ \text{mV}$ ) and by acquisition of full  $I$ - $V$  relationships for steady state activation (200 ms steps from  $-80$  to  $+40\ \text{mV}$  in  $10\ \text{mV}$  increments) or inactivation (2 s inactivation steps from  $-80$  to  $+40\ \text{mV}$  in  $10\ \text{mV}$  increments, a  $10\ \text{ms}$  pre-pulse at  $-80\ \text{mV}$  followed by a single voltage step to  $+60\ \text{mV}$ ). Current magnitude was normalised to cell capacitance as required. Conductance values ( $G$ ) were calculated from the equation  $G = I/(V - \text{EK})$ , where the Nernst equilibrium potential (EK) was calculated as  $-89\ \text{mV}$  at  $37^\circ\text{C}$ . Normalised conductance/voltage profiles for  $K_v$  currents were fitted to a single Boltzmann function with the form  $G = G_{\text{max}}/(1 + \exp[-(V - V_{\text{mid}})/k])$ , where  $G_{\text{max}}$  is the maximal conductance,  $V_{\text{mid}}$  is the test potential for half-maximal conductance ( $G_{0.5}$ ) and  $k$  represents the slope of the activation curve. Patch pipettes had resistances of 4–6  $\text{M}\Omega$ . Series resistance was compensated for (60–80%) after achieving the whole-cell configuration. Signals were sampled at  $10\ \text{kHz}$  and low-pass filtered at  $2\ \text{kHz}$ . Voltage-clamp acquisition and analysis protocols were performed using an Axopatch 200A amplifier/Digidata 1200 interface controlled by Clampex 10.0 software (Molecular Devices, Sunnyvale, CA, USA). Off-line analysis was performed using Clampfit 10.0 (Molecular Devices). Data are expressed as current density ( $\text{pA pF}^{-1}$ ) or  $I/I_{\text{zero}}$ , where  $I_{\text{zero}}$  is the current magnitude recorded at the onset of a given experimental intervention.

### Cell culture and transfection

HEK 293 cells were cultured in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% (v/v) fetal bovine serum and 1% (v/v) penicillin/streptomycin. Cells were transfected following the manufacturer's instructions with  $12\ \mu\text{g}$  of pcDNA3.1 encoding an HA-tagged human  $K_v1.5$  (KCNA5) using Fugene 6 (Promega, Madison, WI, USA) and lysed 48 h later.

### RT-PCR

Total RNA was isolated from frozen canine tissues and from frozen pelleted HEK 293 cells stably expressing  $K_v1.5$ , using the RNeasy Mini Kit (Qiagen, Valencia, CA, USA) as per the manufacturer's instructions. Reverse transcription PCRs (RT-PCRs) were carried out on  $200\ \text{ng}$  of total RNA using the One-Step RT-PCR Kit



(ABM, Richmond, Canada) as recommended in the manual. Then, 20  $\mu\text{l}$  of the 50  $\mu\text{l}$  reaction was run on a 1% agarose gel and visualised using Safe-White (ABM) and a GelDoc equipped with Quantity One software (BioRad, Hercules, CA, USA).  $K_v\beta$  primer sequences were as previously published (Platoshyn *et al.* 2004) and for the reference gene ReadyMade GAPDH primers (Integrated DNA Technologies, Coralville, IA, USA) were used with sequences as follows: GAPDH-For, ACCACAGTCCATGCCATCAC; GAPDH-Rev, TCCACCACCCTGTTGCTGTA. RT-PCR was repeated with 250 ng of template and 35 cycles of PCR after very faint bands were observed in the  $K_v1.5$  stable cell line for  $K_v\beta1$  and  $K_v\beta3$ . Canine ventricle was also repeated for comparison.

### $K_v1.5$ phosphorylation assays

Phosphorylation assays were performed as described previously (Ross *et al.* 2011) using AMPK purified from bacteria and phosphorylated with CAMKK $\beta$  (10 units  $\text{ml}^{-1}$ ) in the presence of 200  $\mu\text{M}$  AMP for 30 min at 30°C.

### Expression, purification and activation of bacterial AMPK

These were performed as described previously (Ross *et al.* 2011).

### Isoform-specific AMPK activities

Isoform-specific AMPK activity was determined by immunoprecipitating tissue lysate with antibodies raised against  $\alpha1$  or  $\alpha2$  subunits bound to protein G-Sepharose beads and quantified using the AMARA peptide and [ $\gamma$ - $^{32}\text{P}$ ]ATP substrates (Cheung *et al.* 2000).

### Statistics

Data are expressed as means  $\pm$  SEM or means  $\pm$  SD, as indicated;  $n$  represents the number of cells tested from at least four different animals. Statistical analysis was performed using Student's  $t$  test for paired observations or one-way ANOVA followed by a Dunnett's *post hoc* test. Differences were considered statistically significant at  $P < 0.05$ .

## Results

### Inhibition of mitochondrial oxidative phosphorylation activates AMPK and reduces $K_v1.5$ current density in pulmonary arterial myocytes

Biguanide drugs such as phenformin inhibit complex I of the mitochondrial respiratory chain (El-Mir *et al.*

2000; Owen *et al.* 2000; Evans *et al.* 2005) and elicit consequent increases in the cellular AMP:ATP ratio and AMPK activation (Hawley *et al.* 2010). Consistent with this, pre-incubation of second- and third-order pulmonary arteries with phenformin (4 h) increased AMPK- $\alpha1$ -associated activity from (mean  $\pm$  S.D.)  $0.025 \pm 0.001$  to  $0.403 \pm 0.012$   $\text{nmol min}^{-1} \text{mg}^{-1}$  protein and AMPK- $\alpha2$ -associated activity from  $0.0096 \pm 0.001$  to  $0.126 \pm 0.006$   $\text{nmol min}^{-1} \text{mg}^{-1}$  protein (Fig. 1A,  $n = 3$ ; 32 arteries, 8 rats). Furthermore, and in accordance with previously reported effects of mitochondrial inhibitors (Firth *et al.* 2008) and hypoxia (Platoshyn *et al.* 2001), pre-incubation of acutely isolated pulmonary arterial myocytes with 1 mM phenformin (2–4 h) also caused pronounced reductions in  $K_v$  current density, from  $126 \pm 17$   $\text{pA pF}^{-1}$  in time-matched controls to  $55 \pm 6$   $\text{pA pF}^{-1}$  at +40 mV (Fig. 1Ca–b,  $n = 9$ –11,  $P < 0.001$ ). Consistent with the effects of phenformin and previous investigations by others (Firth *et al.* 2008), acute application of antimycin A (1  $\mu\text{M}$ ), a rapidly acting inhibitor of complex III, caused equivalent reductions in  $K_v$  current density, from  $131.3 \pm 10.4$  to  $62.6 \pm 11.1$   $\text{pA pF}^{-1}$  at +40 mV (Fig. 1Da–b,  $n = 6$ ,  $P < 0.001$ ). Unless stated, in these and all subsequent experiments on pulmonary arterial myocytes, potassium currents were recorded in the presence of paxilline (1  $\mu\text{M}$ ) to block the large conductance voltage- and calcium-activated  $\text{K}^+$  ( $\text{BK}_{\text{Ca}}$ ) channel.

Given that the contribution to native  $K_v$  currents of  $K_v2.1$  and  $K_v1.5$  varies, in a manner related to both the size and the regional location within the lung of the arteries from which myocytes are derived (Smirnov *et al.* 2002), we assessed the nature of the channels that underpin the  $K_v$  current within the cells under study. Application of the  $K_v1.5$  blocker diphenyl phosphine oxide-1 (DPO-1, 1  $\mu\text{M}$ , Fig. 1B) in the absence of paxilline caused almost total inhibition of the  $K_v$  currents ( $96 \pm 1\%$  at +40 mV;  $n = 6$ ,  $P < 0.0001$ ), consistent with the view that  $K_v1.5$  drives the majority of voltage-gated  $\text{K}^+$  currents in myocytes of the near-resistance-sized pulmonary arteries studied here, which contribute most to the increase in pulmonary vascular resistance during hypoxia (Kato & Staub, 1966; Archer *et al.* 2004).

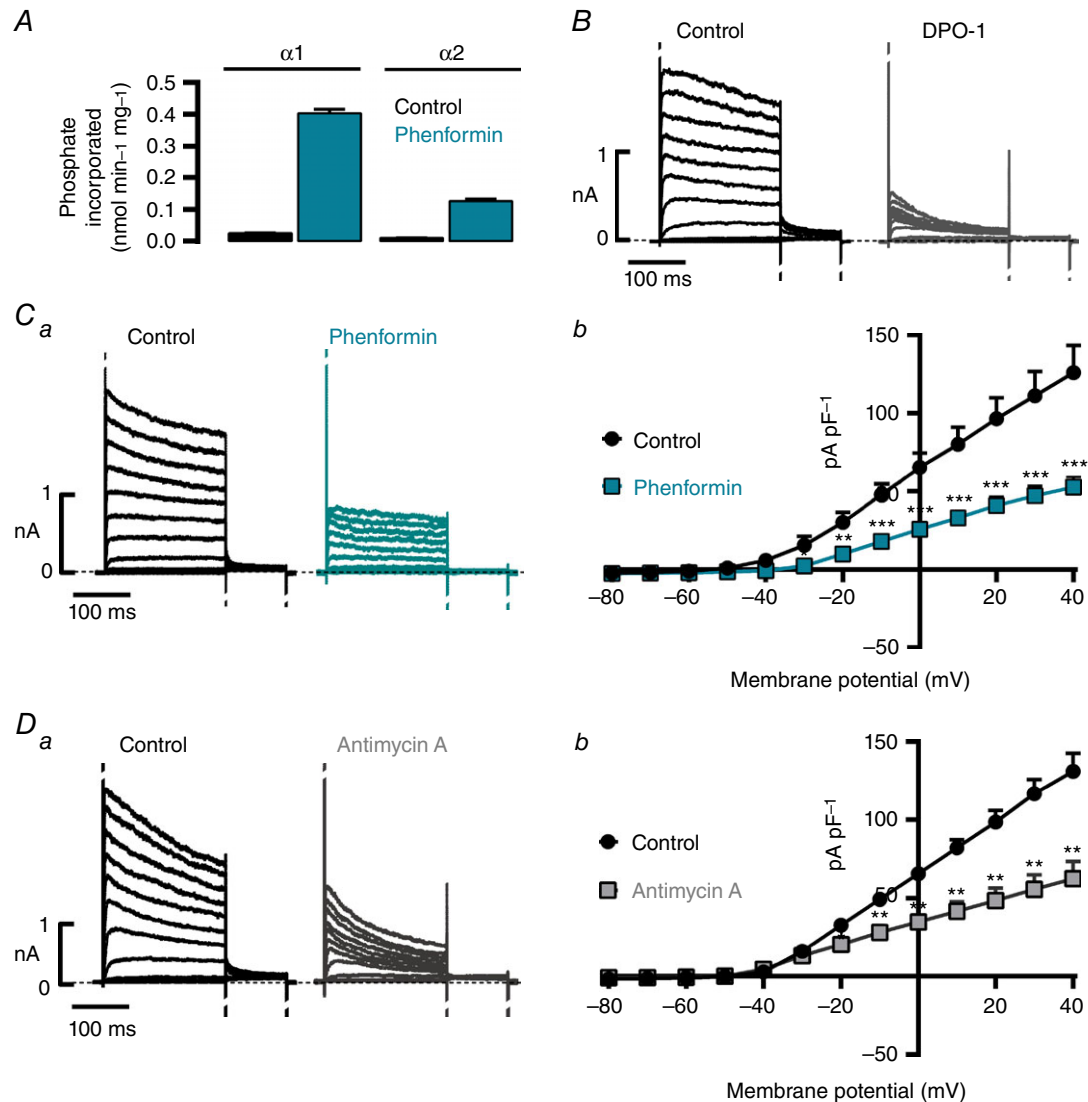
### AMPK activation inhibits $K_v1.5$ currents in pulmonary arterial myocytes

We next assessed the effect on  $K_v1.5$  current amplitude of extracellular application of three AMPK activators with distinct mechanisms of action, i.e. A769662, 5-aminoimidazole-4-carboxamide riboside (AICAR) and C13. Analysis of the time course for  $K_v1.5$  inhibition at steady-state activation (100 ms at +40 mV) showed the time to onset of effect for A769662 (100  $\mu\text{M}$ ), AICAR (1 mM) and C13 (30  $\mu\text{M}$ ) to be around 2 min, with apparent

maxima for inhibition achieved after 8–10 min (Fig. 2B). After 10 min,  $K_v1.5$  currents had declined (Fig. 2A) from  $144 \pm 12$  to  $101 \pm 9$  pA pF<sup>-1</sup> in the presence of A769662 ( $n = 14$ ), from  $186 \pm 23$  to  $136 \pm 17$  pA pF<sup>-1</sup> in the presence of AICAR ( $n = 6$ ) and from  $164 \pm 8$  to  $104 \pm 10$  pA pF<sup>-1</sup> in the presence of C13 ( $n = 8$ ). Note, however, that in 3 of 9 cells superfused with AICAR we observed no effect (excluded from analysis).

Surprisingly, we also observed inhibition of  $K_v1.5$  currents upon application of the non-selective AMPK

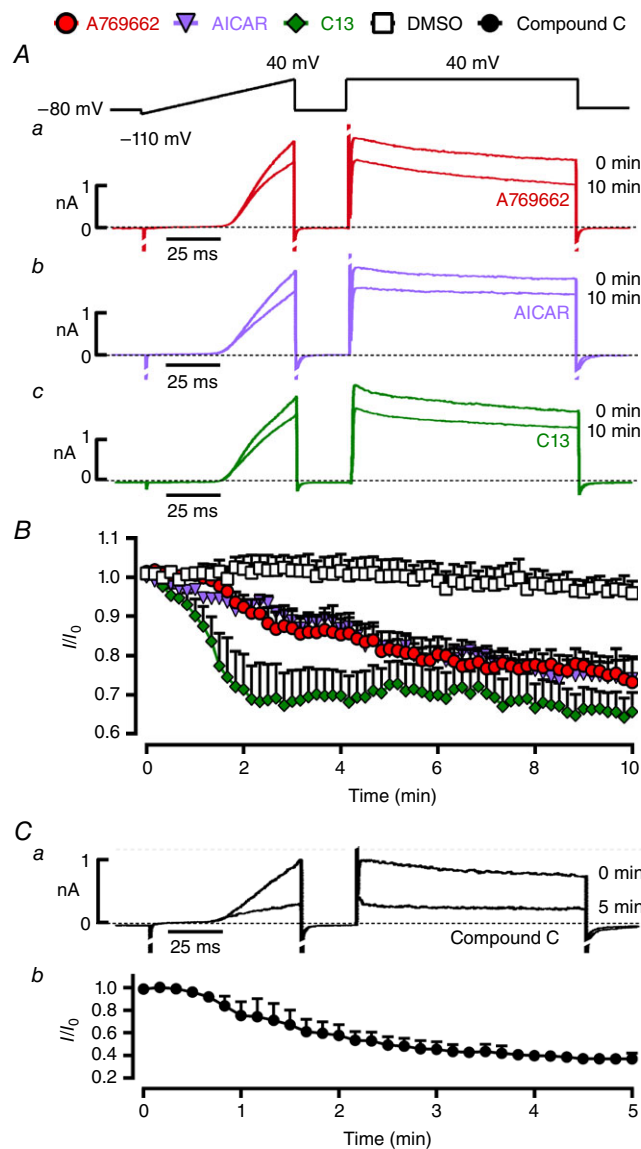
antagonist compound C ( $30 \mu\text{M}$ ), from  $164 \pm 62$  to  $59 \pm 24$  pA pF<sup>-1</sup> ( $n = 3$ ; Fig. 2C); this confounding effect precluded the use of this agent in further studies on myocytes. Previous studies have shown that compound C has little or no effect on resting pulmonary arterial tone, but inhibits acute HPV in a concentration-dependent manner (Robertson *et al.* 2008), which must therefore be induced independently of the inhibition by hypoxia of  $K_v1.5$  inhibition (Dipp *et al.* 2001). It is worth noting that in a screen of 70 protein kinases, at least 10 were



**Figure 1. Inhibition of mitochondrial oxidative phosphorylation activates AMPK and reduces  $K_v1.5$  current density in pulmonary arterial myocytes**

A, bar chart showing the effect of 10 mM phenformin on the activity of AMPK- $\alpha1$  and AMPK- $\alpha2$  containing heterotrimers, as determined by immunoprecipitate kinase assay ( $n = 3$ ; 32 arteries, 8 rats). B, representative records (200 ms pulses from  $-80$  to  $+40$  mV in 10 mV increments, holding potential  $-80$  mV) in pulmonary arterial myocytes before (control) and after extracellular application of  $1 \mu\text{M}$  DPO-1. C and D, representative records (a) and associated  $I$ - $V$  relationships (b; 200 ms depolarization pulses from  $-80$  to  $+40$  mV in 10 mV increments, holding potential  $-80$  mV) from myocytes pre-incubated with 1 mM phenformin versus time-matched controls (C, green,  $n = 9$ –11), or before and after 5–8 min extracellular application of  $1 \mu\text{M}$  antimycin A (D,  $n = 6$ ). \* $P < 0.05$ , \*\* $P < 0.01$  and \*\*\* $P < 0.001$ .

inhibited by compound C more potently than AMPK (Bain *et al.* 2007). Thus, it is not a specific inhibitor of AMPK, a point reinforced by our findings that it markedly attenuates  $K_v1.5$  function. This should be considered when interpreting outcomes of other cell-based assays that have employed compound C, not least with respect to myocyte proliferation and survival (Ibe *et al.* 2013).



**Figure 2. Time course for reduction in  $K_v$  current in response to AMPK activators**

A, representative current records for voltage ramp and step protocol at 0 and 10 min after extracellular application of 100  $\mu$ M A769662 (a), 1 mM AICAR (b) or 30  $\mu$ M C13 (c).

B, time course for reductions in  $K_v$  current during 10 min of extracellular application of DMSO (1:1000, vehicle control), 100  $\mu$ M A769662, 1 mM AICAR and 30  $\mu$ M C13. C, the effect on  $K_v$  currents of pulmonary arterial myocytes of 5 min extracellular application of 30  $\mu$ M compound C (a), and the time course for inhibition (b). Results are expressed as mean  $\pm$  SEM,  $n = 3$ –8.

Importantly, upon equilibration of pulmonary arterial myocytes with AICAR, A769662 and C13, reductions in current density were evident throughout the  $I$ – $V$  range over which  $K_v1.5$  currents were activated (Fig. 3A, B). This was confirmed by the fact that A769662 was without effect on residual currents observed following pre-incubation of cells with DPO-1 even in the absence of paxilline (Fig. 3C), current density measuring  $10 \pm 2$  pA pF $^{-1}$  in the presence of DPO-1 alone and  $11 \pm 3$  pA pF $^{-1}$  in the presence of DPO-1 and A769662 ( $n = 6$ ).

### Intracellular application of active AMPK heterotrimers inhibits $K_v1.5$ in pulmonary arterial myocytes

Although A769662, AICAR and C13 activate AMPK by different mechanisms and are therefore unlikely to have the same off-target effects, we also analysed the effect on endogenous  $K_v1.5$  channel function of bacterially expressed human AMPK heterotrimers ( $\alpha 2\beta 2\gamma 1$  or  $\alpha 1\beta 1\gamma 1$  complexes). These had been thiophosphorylated at Thr172 using CaMKK $\beta$  to yield active, recombinant AMPK that is also resistant to phosphatases (Ross *et al.* 2011). Intracellular dialysis of either of the active  $\alpha 2\beta 2\gamma 1$  or  $\alpha 1\beta 1\gamma 1$  heterotrimers (Fig. 4A) evoked  $K_v1.5$  current inhibitions that were similar in magnitude ( $-33 \pm 5\%$  for  $\alpha 2\beta 2\gamma 1$  and  $-36 \pm 7\%$  for  $\alpha 1\beta 1\gamma 1$  at +40 mV;  $n = 5$ –7) to the reductions induced by pharmacological activation of AMPK. Importantly, current inhibition was not observed upon intracellular dialysis of an inactive AMPK heterotrimer [Fig. 4B;  $\alpha 2\beta 2\gamma 1$  complex with D157A mutation in  $\alpha 2$  (Ross *et al.* 2011)]. Based on the use both of pharmacological activation of endogenous AMPK and of exogenous recombinant AMPK, we can conclude that AMPK mediates, either directly or indirectly, inhibition of  $K_v1.5$  currents in pulmonary arterial myocytes.

### Hypoxia and mitochondrial inhibitors attenuate $K_v1.5$ currents and occlude further current inhibition by AMPK activation

AMPK is intimately coupled to mitochondrial metabolism through changes in the AMP:ATP and ADP:ATP ratios (Gowans *et al.* 2013), which is evident from the fact that AMPK activity was increased by hypoxia (Evans *et al.* 2005) and by the mitochondrial inhibitor phenformin (Fig. 1A). To assess whether AMPK acted as a downstream mediator of  $K_v1.5$  inhibition during hypoxia and inhibition of mitochondrial oxidative phosphorylation, we therefore carried out studies to determine if  $K_v1.5$  inhibition by these stimuli was additive with respect to that induced by AMPK activators.

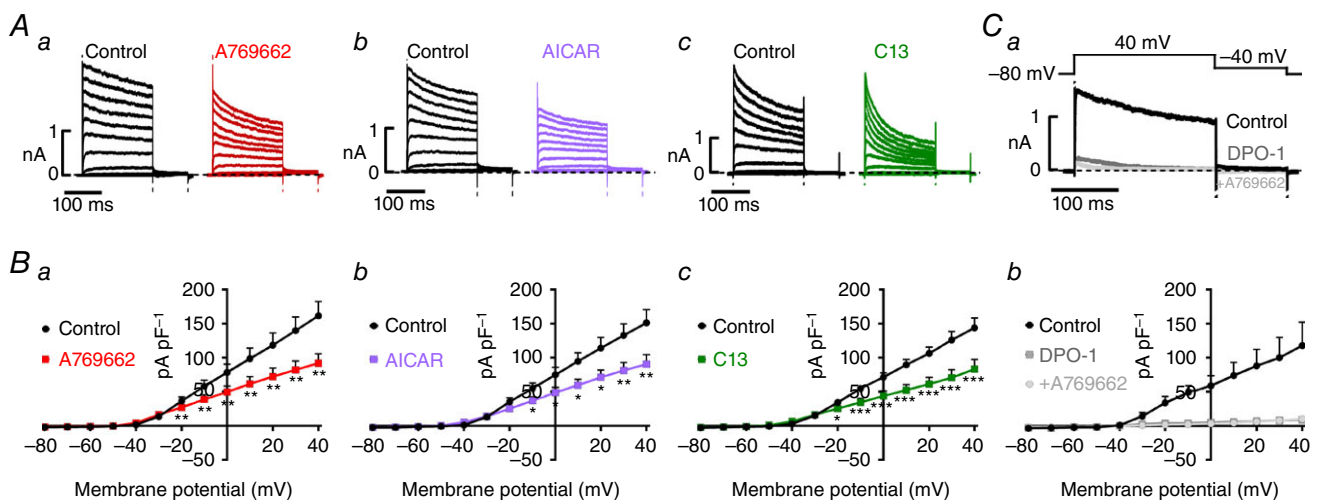
Superfusion of pulmonary arterial myocytes with a hypoxic solution ( $\sim 4\%$  O $_2$ , > 10 min) markedly inhibited  $K_v1.5$  currents, with a maximal reduction achieved after

~10 min (Fig. 5A, B,  $150 \pm 9$  pA pF<sup>-1</sup> during normoxia vs.  $63 \pm 6$  pA pF<sup>-1</sup>,  $n = 14$ –19, after 10–40 min of hypoxia;  $P < 0.001$ ). Most importantly, continued hypoxia markedly attenuated the degree of  $K_v1.5$  inhibition upon application of  $100 \mu\text{M}$  A769662, which reduced current density from  $53 \pm 4$  pA pF<sup>-1</sup> during hypoxia alone to  $45 \pm 5$  pA pF<sup>-1</sup> ( $n = 6$ ,  $P < 0.05$ ; Figs 5B, C and 6A). As described previously, pre-incubation of acutely isolated myocytes with 1 mM phenformin (2 h) also caused pronounced reductions in  $K_v$  current density, from  $126 \pm 17$  to  $55 \pm 6$  pA pF<sup>-1</sup> at +40 mV (Fig. 1Ca–b,  $n = 9$ –11,  $P < 0.001$ ). Moreover, and consistent with the effects of hypoxia, pre-incubation of cells with phenformin markedly attenuated the degree to which  $K_v1.5$  currents were inhibited upon application of A769662, which reduced current density from  $57 \pm 12$  pA pF<sup>-1</sup> in the presence of phenformin alone to  $49 \pm 10$  pA pF<sup>-1</sup> (Figs 5Cb and 6A;  $n = 4$ ,  $P = 0.09$ ). In this respect antimycin A was equally effective, A769662 reducing  $K_v1.5$  current density from  $44 \pm 4$  pA pF<sup>-1</sup> in the presence of antimycin A alone to  $33 \pm 4$  pA pF<sup>-1</sup> (Figs 5Cc and 6A;  $n = 3$ ,  $P < 0.05$ ). Therefore,  $K_v1.5$  inhibition by pharmacological AMPK activation is non-additive with respect to the action of either hypoxia or respiratory poisons. We can therefore conclude that in myocytes from near-resistance-sized pulmonary arteries, AMPK probably acts as the primary downstream mediator of  $K_v1.5$  channel inhibition not only during hypoxia, but also in response to the inhibition of mitochondrial oxidative phosphorylation.

### AMPK activators induce a leftward shift in the $I$ – $V$ relationship for $K_v1.5$ current activation that is occluded by hypoxia and mitochondrial inhibitors

AMPK activation not only reduced  $K_v1.5$  current density in pulmonary arterial myocytes throughout the  $I$ – $V$  range over which  $K_v1.5$  currents were activated, but also induced a significant 12–14 mV hyperpolarizing shift in the activation curve (Fig. 6B, C) analysed as  $G/G_{\text{max}}$  and fitted to a single Boltzmann function.  $V_{\text{mid}}$  measured:  $-17.9 \pm 1.2$  and  $-30.5 \pm 4.5$  mV in the absence and presence of AICAR, respectively;  $-17.4 \pm 1.6$  and  $-30.2 \pm 3.5$  mV in the absence and presence of A769662;  $-20.9 \pm 2.6$  and  $-39.7 \pm 4.6$  mV in the absence and presence of C13 ( $n = 5$ –7,  $P < 0.01$ ). To allow for direct comparison of the maximal effect of each of these agents, we also expressed the leftward shift as the net change in  $V_{\text{mid}}$  (Fig. 6B);  $\Delta V_{\text{mid}}$  was  $-12.6 \pm 4.8$ ,  $-12.7 \pm 2.4$  and  $-18.7 \pm 2.3$  mV, respectively, for AICAR, A769662 and C13. As previously observed for current inhibition, the leftward shift in the  $I$ – $V$  range for  $K_v1.5$  activation that was induced by AMPK activation was non-additive with respect to the effect of hypoxia and prior inhibition of mitochondrial oxidative phosphorylation,  $\Delta V_{\text{mid}}$  for A769662 measuring  $-4.5 \pm 0.9$  mV in the presence of hypoxia and  $-3.7 \pm 0.6$  mV in the presence of antimycin A.

To explore further the functional significance of a leftward shift in the  $I$ – $V$  relationship we assessed the voltage-dependence of both  $K_v1.5$  activation and inactivation in the absence and presence A769662, and



**Figure 3. AMPK activation inhibits  $K_v1.5$  currents in pulmonary arterial myocytes**

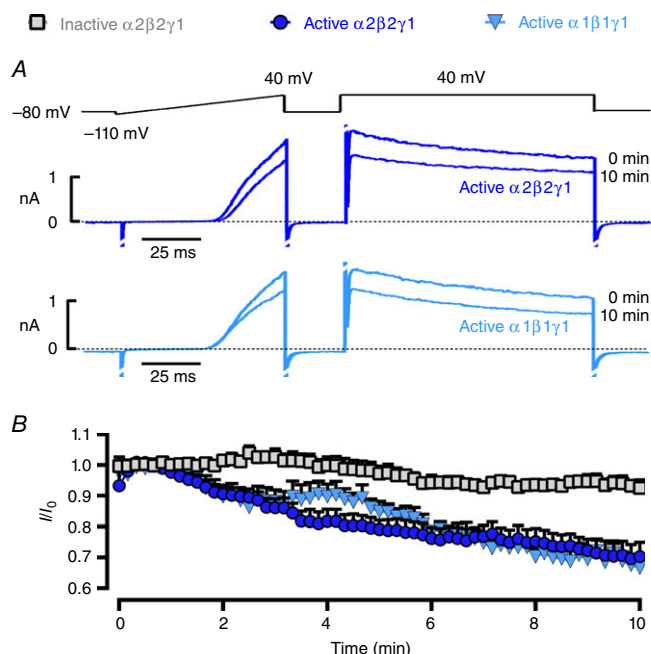
A, representative current traces (200 ms depolarization pulses from  $-80$  to  $+40$  mV in 10 mV increments, holding potential  $-80$  mV); and B,  $I$ – $V$  relationships for  $K_v$  current recorded before (control) and after extracellular application of A769662 (a,  $100 \mu\text{M}$ ), AICAR (b, 1 mM) or C13 (c,  $30 \mu\text{M}$ ); measurements taken at end of pulse. C, representative current traces (a) and  $I$ – $V$  relationships (b) for  $K_v$  currents in the absence and presence of  $1 \mu\text{M}$  DPO-1 and the effect of  $100 \mu\text{M}$  A769662 in the continued presence of DPO-1. Results are expressed as mean  $\pm$  SEM,  $n = 5$ –7. \* $P < 0.05$ , \*\* $P < 0.01$  and \*\*\* $P < 0.001$ .



thus determined the effect of AMPK activation on the window current, i.e. the proportion of current at a given potential that is never inactivated. Figure 7 clearly shows that AMPK activation by A769662 induced a leftward shift in  $K_v1.5$  activation and inactivation curves and thus of the window current, lowering the threshold for activation while reducing the available non-inactivating current.

### AMPK phosphorylates $K_v1.5$ and reduces $K^+$ currents carried by recombinant $K_v1.5$ channels stably expressed in HEK 293 cells

To determine whether AMPK modulates  $K_v1.5$  channel function directly, we examined the effects of AMPK activation on human  $K_v1.5$  channels stably expressed in HEK 293 cells. Application of A769662 (100  $\mu$ M) reduced  $K^+$  currents carried by recombinant human  $K_v1.5$  (Fig. 8Aa) in a manner that was blocked by the non-selective AMPK inhibitor compound C (40  $\mu$ M, Fig. 8B). Moreover, intracellular dialysis of active AMPK  $\alpha2\beta2\gamma1$  or  $\alpha1\beta1\gamma1$  heterotrimers also reduced  $K_v1.5$  currents, which remained unaffected in the presence of an inactive (D157A mutant)  $\alpha2\beta2\gamma1$  heterotrimer

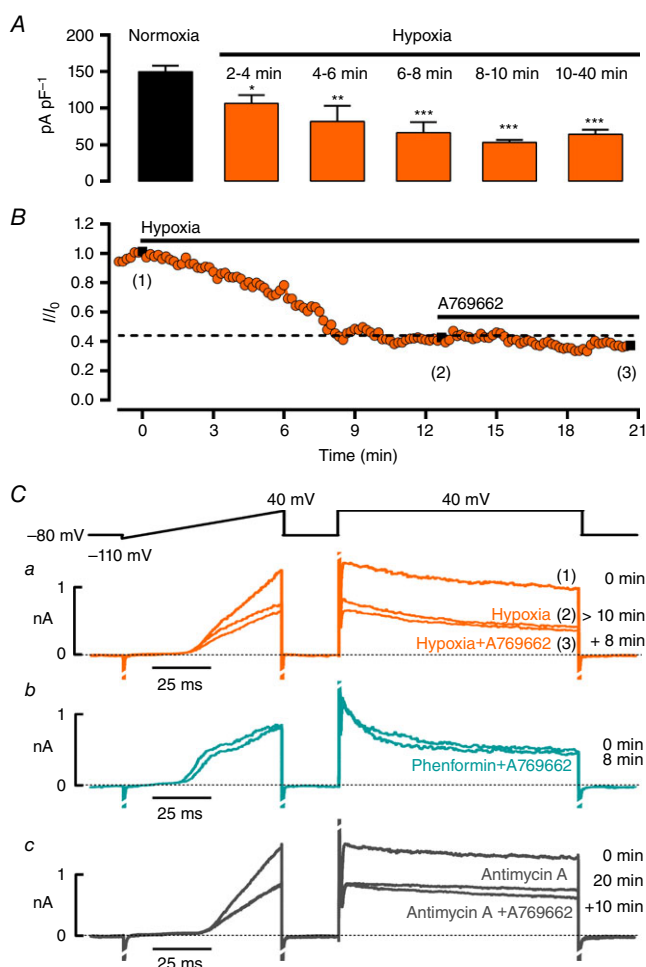


**Figure 4. Intracellular application of active AMPK heterotrimers inhibits  $K_v1.5$  in pulmonary arterial myocytes**

A, voltage ramp and step protocol recorded at 0 and 10 min after intracellular dialysis of the indicated recombinant, thiophosphorylated active AMPK heterotrimers ( $\alpha2\beta2\gamma1$  or  $\alpha1\beta1\gamma1$ ). B, time course for reduction in  $K_v$  current following intracellular dialysis of either active  $\alpha2\beta2\gamma1$  (thiophosphorylated, 5 U ml<sup>-1</sup>), active  $\alpha1\beta1\gamma1$  (thiophosphorylated, 5 U ml<sup>-1</sup>) or inactive  $\alpha2\beta2\gamma1$  (D157A mutant) AMPK heterotrimer. Results are expressed as mean  $\pm$  SEM,  $n = 5-7$ .

(Fig. 8Ab–C). Like pulmonary arterial myocytes, therefore, currents carried by human  $K_v1.5$  expressed in HEK 293 cells were similarly inhibited both by AMPK activators and by intracellular dialysis of recombinant active AMPK heterotrimers (Fig. 8D).

We also examined whether AMPK directly phosphorylates  $K_v1.5$ , using as substrate the human protein immunoprecipitated from these HEK 293 cells.



**Figure 5. Hypoxia and mitochondrial inhibitors attenuate  $K_v1.5$  currents and occlude further current inhibition by AMPK activation**

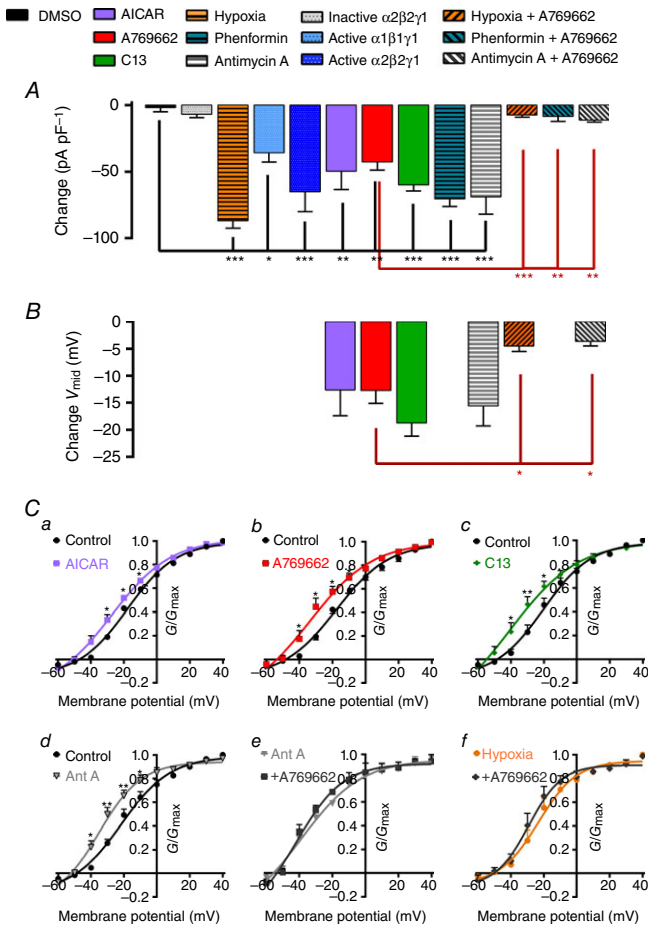
A, bar chart showing the reduction in current density at +40 mV from myocytes superfused with a hypoxic solution (4%  $O_2$ ;  $n = 4-19$ ). B, time course for reduction in  $K_v$  current during extracellular superfusion with hypoxic solution and the effect of subsequent addition of 100  $\mu$ M A769662; measurements taken at the end of a 100 ms step pulse to +40 mV. Ca, example records for voltage ramp and step protocol under normoxia (1), > 10 min of hypoxia (2), after 8 min of superfusion with hypoxia + 100  $\mu$ M A769662 (3). Cb-c, as in a but representative current traces show the effect of 100  $\mu$ M A769662 on myocytes pre-incubated with 1 mM phenformin (b) or after 20 min extracellular application of 1  $\mu$ M antimycin A (c). \* $P < 0.05$ , \*\* $P < 0.01$  and \*\*\* $P < 0.001$  vs. normoxia.

We first treated the immunoprecipitate with recombinant protein phosphatase (PP1 $\gamma$ ) to remove endogenous phosphate groups, then phosphorylated with purified rat liver AMPK (a mixture of  $\alpha1\beta1\gamma1$  and  $\alpha2\beta1\gamma1$  isoforms) and [ $\gamma$ - $^{32}$ P]ATP in the presence and absence of 200  $\mu$ M AMP. The stoichiometry of phosphorylation was estimated by cutting out and counting the  $^{32}$ P-labelled band and estimating the protein content by comparison

with serum albumin standards run on the same gel. We obtained estimates of 0.57 and 0.13 moles of phosphate per mole of protein in the presence and absence of AMP (data not shown). We repeated the experiment using recombinant human  $\alpha1\beta1\gamma1$  and  $\alpha2\beta2\gamma1$  complexes expressed in bacteria, and obtained stoichiometries of 0.7 and 1.6 moles of phosphate per mole of protein respectively (Fig. 8E, we did this only in the presence of AMP because, for reasons that remain unclear, the bacterially expressed complexes are much less AMP-dependent). While we have not yet determined the number and identity of the sites phosphorylated on  $K_v1.5$ , these results indicate that different AMPK complexes can catalyse a substantial AMP-activated phosphorylation of  $K_v1.5$  in cell-free assays.

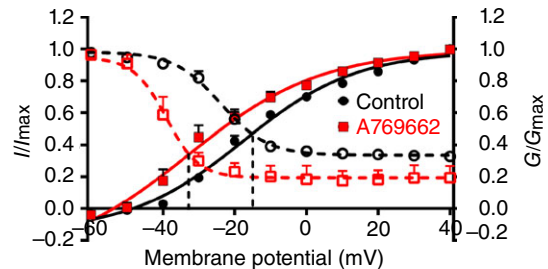
## Discussion

The present investigation describes, for the first time, evidence that AMPK couples  $K_v1.5$  channel function (defined by the  $K_v1.5$  blocker DPO-1) to the inhibition by hypoxia of mitochondrial metabolism in pulmonary arterial myocytes. Consistent with this proposal, inhibition by phenformin or hypoxia of the mitochondrial electron transport chain (El-Mir *et al.* 2000; Owen *et al.* 2000) increases NAD(P)H autofluorescence (Evans *et al.* 2005), activates AMPK and inhibits  $K_v$  currents in pulmonary arterial myocytes. That AMPK activation may specifically regulate  $K_v1.5$  in response to metabolic stresses such as hypoxia gained further support from our findings that AMPK activators that are structurally distinct and have different mechanisms of action, namely A769662, AICAR and C13, all markedly inhibited  $K_v$  currents in pulmonary arterial myocytes. A769662, which primarily causes allosteric activation (Goransson *et al.* 2007; Scott *et al.* 2014), binds in a site located between the  $\alpha$  and  $\beta$  subunits of AMPK (Xiao *et al.* 2013). AICAR (Corton *et al.* 1995) and C13



**Figure 6. Comparison of the change in current density and voltage-conductance relationships induced by activated AMPK and AMPK activators in pulmonary arterial myocytes**

A, bar chart showing mean  $\pm$  SEM change in current density at the end of each experimental intervention after 6–10 min of DMSO (1:1000), inactive  $\alpha2\beta2\gamma2$ , hypoxia ( $\sim 4\%$   $O_2$ ), 5 U active  $\alpha2\beta2\gamma2$ , 5 U active  $\alpha1\beta1\gamma1$ , 1 mM AICAR, 100  $\mu$ M A769662, 30  $\mu$ M C13, 1 mM phenformin (2–4 h), 1  $\mu$ M antimycin A, 100  $\mu$ M A769662 in the presence of hypoxia ( $\sim 4\%$   $O_2$ , > 10 min), phenformin and antimycin A ( $n = 3$ –16). B, similar to A but showing the net change in  $V_{mid}$  of the voltage-conductance plots for 1 mM AICAR, 100  $\mu$ M A769662, 30  $\mu$ M C13, 1  $\mu$ M antimycin A, 100  $\mu$ M A769662 in the presence of 1  $\mu$ M antimycin A and 100  $\mu$ M A769662 in the presence of hypoxia ( $\sim 4\%$   $O_2$ , > 10 min);  $n = 3$ –7. C, voltage-conductance plots showing effects of 1 mM AICAR (a), 100  $\mu$ M A769662 (b), 30  $\mu$ M C13 (c), 1  $\mu$ M antimycin A (d), 100  $\mu$ M A769662 in the presence of 1  $\mu$ M antimycin A (e) and 100  $\mu$ M A769662 in the presence of hypoxia (f,  $\sim 4\%$   $O_2$ , > 10 min). Results are expressed as mean  $\pm$  SEM,  $n = 3$ –7. \* $P < 0.05$ , \*\* $P < 0.01$  and \*\*\* $P < 0.001$ .

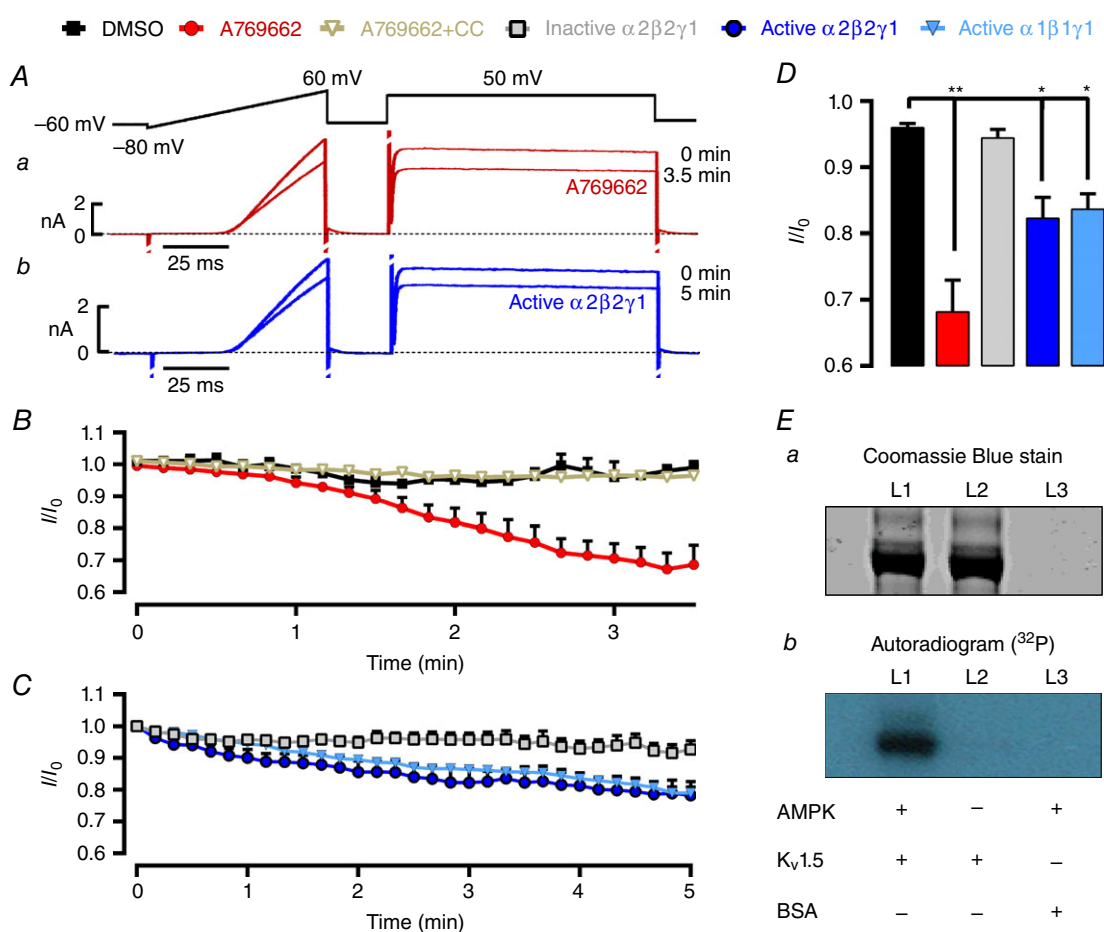


**Figure 7. A769662 induces a leftward shift in the activation and inactivation curves of  $K_v1.5$**

Plot shows the voltage-conductance relationship for  $K_v1.5$  activation and inactivation in the absence (control, black) and presence of 100  $\mu$ M A769662 (red). Activation is indicated by filled symbols and continuous lines; inactivation is indicated by open symbols and dashed lines. Data points are mean  $\pm$  SEM ( $n = 3$ –6). Curves were obtained by fitting to the sigmoidal Boltzmann equation.

(Gomez-Galeno *et al.* 2010) act similarly in the sense that they are both taken up into cells and converted to molecules (ZMP and C2, respectively) that bind to the  $\gamma$  subunit, mimicking the effects of AMP. However, C2 is a much more potent activator of AMPK than ZMP and, unlike the latter, does not affect other AMP-sensitive enzymes such as glycogen phosphorylase or fructose-1,6-bisphosphatase (Hunter *et al.* 2014). Moreover, A769662 is selective for complexes containing the  $\beta 1$  subunit (Scott *et al.* 2008), while C2 is selective for complexes containing the  $\alpha 1$  subunit (Hunter *et al.* 2014). These data suggest that  $K_v1.5$  current inhibition in pulmonary arterial myocytes may be delivered in whole or in part by AMP-dependent activation of heterotrimer

containing  $\alpha 1$  and  $\beta 1$ . Furthermore, inhibition of  $K_v1.5$  by hypoxia or by pre-incubation with inhibitors of mitochondrial oxidative phosphorylation prevented further current reduction by AMPK activators, suggesting that AMPK may act as the primary regulator of  $K_v1.5$  downstream of inhibition of mitochondrial oxidative phosphorylation during hypoxia. This conclusion is also supported by previous findings that hypoxia activates AMPK (Evans *et al.* 2005) and achieves maximal AMPK phosphorylation within  $\sim 10$  min (Ibe *et al.* 2013). Crucially, given the possible off-target effects of any pharmacological agents, intracellular dialysis of active and phosphatase-resistant (thiophosphorylated) recombinant AMPK heterotrimers selectively inhibited  $K_v$  currents in







signalling pathway may predispose individuals to hypoxia and other forms of pulmonary arterial hypertension (Bonnet *et al.* 2006). In this respect, it is interesting to note that single nucleotide polymorphisms (SNPs) in the gene encoding  $K_v1.5$  predispose to pulmonary hypertension and reduce  $K_v1.5$  channel availability in pulmonary arterial myocytes (Remillard *et al.* 2007), raising the intriguing possibility that this may be due, at least in part, to alterations in AMPK-dependent regulation of  $K_v1.5$ .

AMPK phosphorylates target proteins containing a  $\Phi(X,\beta)XXS/TXXX\Phi$  ( $\Phi$ , hydrophobic;  $\beta$ , basic) recognition motif (Hardie *et al.* 2016). The protein sequence for  $K_v1.5$  presents 15 serines and 4 threonines susceptible to phosphorylation by serine–threonine kinases (Blom *et al.* 1999). However, none of these represents good matches to the consensus recognition sites for AMPK (<http://scansite3.mit.edu>), despite the fact that our studies on  $^{32}P$  phosphorylation indicate that the immunoprecipitated channel protein might be a direct substrate for AMPK. This raises two distinct possibilities, (1) AMPK recognises non-canonical sites within the  $K_v1.5$  sequence, as has been shown for other proteins (Jones *et al.* 2005; Chang *et al.* 2009; Egan *et al.* 2011); or (2) AMPK phosphorylates one or more associated protein(s), such as the regulatory  $\beta$  subunits. The fact that AMPK phosphorylates and regulates  $K_v1.5$  suggests that its effects are mediated, at least in part, independently of such interactions. Nevertheless, we cannot rule out the possibility that outcomes may be modulated by the  $\beta$  subunits, given that rat pulmonary arterial myocytes express  $K_v\beta1$ ,  $K_v\beta2$  and  $K_v\beta3$  (Platoshyn *et al.* 2006) and phosphorylation of either  $K_v1.5$  or regulatory  $K_v\beta$  subunits may modulate not only channel gating and inactivation kinetics (Holmes *et al.* 1996; Williams *et al.* 2002) but also the sensitivity of  $K_v1.5$  to regulation by  $K_v\beta$  subunits (Kwak *et al.* 1999; David *et al.* 2012; Macias *et al.* 2014). It is equally plausible that AMPK-dependent phosphorylation of  $K_v1.5$  in pulmonary arterial myocytes may alter  $K_v\alpha$ – $K_v\beta$  interactions, sensitivity to metabolic stress, channel trafficking (Martens *et al.* 1999; Tipparaju *et al.* 2012) and/or degradation via ubiquitin ligases (Mia *et al.* 2012; Andersen *et al.* 2015). Further studies will be aimed at identifying the AMPK phosphorylation sites on  $K_v1.5$  and on associated  $\beta$  subunits.

In conclusion, we propose that AMPK couples the inhibition of mitochondrial oxidative phosphorylation to  $K_v1.5$  channel inhibition in pulmonary arterial myocytes, which may contribute to the regulation by AMPK of smooth muscle proliferation and thus to the development of pulmonary hypertension. In addition, AMPK-dependent modulation of  $K_v1.5$  channel availability may also contribute to proliferative potential associated with other diseases, such as cancer (Bonnet *et al.* 2007; Comes *et al.* 2013; Vallejo-Gracia *et al.* 2013).

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## Additional information

### Competing interests

None of the authors have any disclosures.

### Author contributions

This manuscript was written by J.M-S. and A.M.E.. All authors contributed to the conception and design or analysis and interpretation of data, and the drafting of the article or revising it critically for important intellectual content. All authors provided final approval of the version to be published. In particular, the idea for the study was conceived by A.M.E. Tissue collection and isolation of pulmonary arterial smooth muscle cells were done by J.M-S. J.M-S. completed all electrophysiology on pulmonary arterial myocytes. A.M.D. completed electrophysiology on HEK293 cells. AMPK trimers were provided by D.G.H. Immunoprecipitate kinase assays and phosphorylation assays were done by F.A.R.. D.F and J.E. generated the HEK293 cell line that stably expressed h $K_v1.5$  and analysed the expression of  $K_v\beta$  in these cells. Studies were conducted at the Centre of Integrative Physiology (University of Edinburgh, Edinburgh, UK), College of Life Sciences (University of Dundee, Dundee, UK) and Department of Anaesthesiology, Pharmacology and Therapeutics, University of British Columbia (Life Sciences Centre, Vancouver, Canada). All authors revised and approved the final version of the manuscript.

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